GEOTECHNICAL BASELINE REPORT

Devil's Slide Tunnel Project

For

The California Department of Transportation

Prepared by:

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1.0 Introduction

1.1 General

The California Department of Transportation (Caltrans) is building twin highway tunnels through the Devil's Slide area just south of the City of Pacifica in the County of San Mateo, California. Design of this project, the Devil's Slide Tunnel (DST) project, has been performed under the direction of HNTB Corporation, the prime consultant, with Earth Mechanics, Inc. (EMI) as the lead Geotechnical Engineer, and ILF Consultants, Inc. as the lead Tunnel Engineer.

1.2 Purpose and Limitations

For purpose and limitations of the Geotechnical Baseline Report (GBR), see Section 6-2 of Special Provision in Section 6, Initial Lining Construction.

2.0 Project Description

2.1 General

Dimensions for structure elements listed in this Section are approximate for illustration purpose only. For bidding purpose, Bidders shall use the actual dimensions shown on the Contract Plans.

2.2 Project Location

The project site is located just south of the City of Pacifica. The north end of the project is 2400 meters (1.5 miles) south of the south end of Pacifica. The new 2-lane roadway leaves Route 1 and crosses over the Shamrock Ranch valley on twin one-lane bridges over a distance of about 365 meters (1200 feet) to the North Portals of the twin one-lane tunnels. The tunnels extend beneath San Pedro Mountain about 1250 meters (4100 feet) to the South Portals. From the South Portals the roadway rejoins Route 1 over a distance of about 500 meters (1600 feet), near the future Disposal Area and Operations and Maintenance Center (OMC) building.

2.3 Project Elements

The Devil's Slide Tunnels consists of a separated two-lane road, one lane in each direction, which passes through twin tunnels and over twin bridges and then connects with the existing non-separated two-lane road at each end. The length of the entire project is approximately 1900 meters, made up of five major project sections that are described in the following paragraph, moving from south to north. Please note that only item 2, 3, and 5 are in this contract, and South Rock Cut (SRC) and bridges are to be constructed in other two separate contracts.

1. Operations and Maintenance Center (OMC) area, the 250-meter-long south approach roadways, excluding the South Rock Cut, extend to the tunnels' South Portals,
2. SRC soil nailing wall.
3. Twin tunnels are 1250 meters long and extend to the North Portals near the south abutments of the twin bridges,
4. Twin bridges are 275 and 300 meters long respectively and span the Shamrock Ranch valley, and
5. North approach roadways that rejoin the existing highway.

The horseshoe-shaped tunnels are generally 9 meters wide, 6.8 meters high and enlarged at the southern South Bound (SB) and Northern North Bound (NB) portals. The SB and NB tunnels are approximately 18 meters apart. There are nine cross passages, an Emergency Vehicle Cross Passage, three equipment chambers with emergency accesses to the Main Tunnels. The tunnels are vented by jet fans and have lighting, fire protection, and operation and control systems.

Excavated materials will be placed in a specified disposal area, located south of the tunnels, which will be the site of future Operation and Maintenance Center.

Each tunnel has a vertical clearance of 4.75 m and provides a single 3.6 meter wide traveled way, two shoulder areas (2.4 m and 0.6 m wide), and two 1.2 m wide sidewalks, for a total width of 9.0 m. The ventilation jet fans are placed in the crown of the tunnel and cross passages are provided about every 120 m.

The design and construction of the tunnels is based on the philosophy of sequential excavation method, also called New Austrian Tunneling Method (NATM) in this report. Depending on ground conditions along the alignment, the initial support system may include shotcrete, rock dowels, lattice girders, spiles, and grouted steel pipes in various combinations shown in the Contract Documents. The final lining is cast-in-place reinforced concrete lining, with a waterproofing membrane and drainage system placed between the initial and final linings.

3.0 Project Geologic Setting

3.1 Site Exploration and Testing Program

Field studies of the project site include a feasibility study performed by Woodward Clyde Consultants (WCC) in 1996, a site reconnaissance and mapping investigation performed by EMI in 2001, and a geotechnical investigation by EMI in 2002. The locations of borings, trenches, downhole testing, and installations are shown on the plan sheet L1.1.

The 1996 WCC study consisted of geologic mapping, 14 rock borings, inclinometer and standpipe installations, seismic refraction surveying and downhole and laboratory testing of rock core.

The 2001 EMI investigation included a compilation and review of data from previous investigations, geologic mapping, including both project and areal mapping, and detailed mapping and plotting of rock discontinuities near the North and South Portals. This investigation confirmed some of the 1996 feasibility investigation geological interpretations but also revealed significant differences, especially in the location and pattern of block-boundary faults and consequently, in the lithology and geologic structure expected to be present in the northern portion of the tunnel.

The 2002 EMI investigation included 21 rock borings, downhole and laboratory testing of rock core, trenching and additional geologic mapping. Data from this investigation is detailed in the Geologic and Geotechnical Data Report (EMI, 2002), referred to as “GDR” in this report.

3.2 Physiography

The project site is located on the central California coastline west of the central San Francisco Bay in a mountainous terrain and landslide complex that forms the seaward termination of the northwest-aligned San Pedro Mountain ridge. Resistant beds of massive sandstone and conglomerate form the crest of the ridge. The southwest flank of the ridge is eroded into the underlying, mostly deeply weathered, Montara quartz diorite. Local resistant zones within the quartz diorite form promontories along the coastline opposite and south of the project. The North Portals of the tunnels will be located in a northeast-aligned spur ridge along the north flank of San Pedro Mountain ridge. The South Portals will be set into the north wall of an alcove-like canyon eroded into the south flank of San Pedro Mountain ridge. The lower part of this alcove is partly occupied by the road-fill embankment for Route 1, which will provide the approach carrying this road into the South Portals of the tunnels.

3.3 Regional Geology and Tectonics

The project site lies along the western margin of the active San Andreas fault system on the San Francisco Peninsula, between the San Andreas and San Gregorio faults. The San Andreas and the San Gregorio faults are northwest-trending, right lateral strike-slip faults that exhibit distinctive patterns transpressional and transtensional deformation along their principal traces and within the adjacent crust; these patterns vary along strike.

The site is about 2.8 km east of the offshore trace of the San Gregorio fault and 7.2 km west of the surface trace of the San Andreas fault. The project will be constructed in a mountainous, highly deformed terrane of Mesozoic-age crystalline igneous (granitic-like) rock overlain by a series of thrust sheets consisting of granitic rock and late-Cretaceous- and early-Tertiary-age clastic sedimentary rock. The thrust and high-angle faults cutting across the project area do not appear to have originated in response to the modern San Andreas fault system.

3.4 Seismicity

The pattern of seismicity in the San Francisco Bay region during the late Quaternary corresponds generally to the regional fault pattern. Among regional scale faults the seismic sources of most significance for the project are the local reaches of the San Andreas and San Gregorio faults.

The peninsula reach of the San Andreas fault has produced major earthquakes at average intervals of around 150 to 250 years. The USGS Working Group on California Earthquake Probabilities has estimated a 21% probability of a strong earthquake (>M6.7) occurring on the peninsula section of the San Andreas fault within the next 30 years.

The most recent damaging shock to originate on this part of the San Andreas fault was the M5.3 San Francisco earthquake of 1957. The maximum earthquake possible on this reach of the San Andreas fault is estimated to be M8.0.

No significant earthquakes have occurred along the northern San Gregorio fault during historic time. Paleoseismic studies along the onshore trace south of Seal Cove have revealed evidence of two large surface-faulting earthquakes (slip>3m) during the past 600 to 1,320 years. The maximum earthquake considered possible for this fault is about M7.5.

The Point San Pedro-Devil's Slide area is the site of persistent microseismic activity occurring in the underlying crust at depths of 6 to 8 km. Earthquakes from this cluster of activity are sometimes felt locally and have been recorded with magnitudes as large as M3.6. No clear relationship has been established between these small shocks and any geologic structures recognized at the surface.

3.5 Stratigraphy and Lithology

The stratigraphy of the site is shown on the longitudinal section along tunnel alignment in Figure 1. It consists generally of Mesozoic granitic basement rock, and a structurally overlying complex of early Tertiary clastic sedimentary rocks. For purposes of reference and description, a system of three block units for the sedimentary rocks and the granitic basement unit is used: "South" (granitic rock), "Central," and "North" Block units.

The blocks are juxtaposed across principal faults of substantial displacements; the principal faults that cross the tunnels' alignment, listed from south to north, are referred to for the purposes of the DST project as faults "A", "B", "02-5" and "C".

3.5.1 South Block

The South Block is located between the South Portal and Fault B. It consists entirely of crystalline igneous rock that has been altered by hydrothermal activity, secondary calcite mineralization, mylonitization and mechanical degradation by pervasive fracturing and local faulting and intense shearing, and weathering. In addition to the protolith quartz diorite, the unit contains late magmatic stage irregular dikes of quartz and felsite. Petrographic analyses of samples show the unit locally ranges in composition from granodiorite to quartz diorite, referred to only as quartz diorite, crystalline igneous or granitic rock.

In the South Block, the quartz diorite can be subdivided into three categories. The quartz diorite of the Fault A hanging wall is characteristically pervasively fractured and weathered, so that it seldom forms natural outcrops. In a zone directly underlying Fault A, the footwall quartz diorite consists of weak, mylonitized rock. At the south portal the footwall quartz diorite is relatively unsheared, moderately strong, pervasively jointed rock forming rock slope and east-facing rock slope.

The Quartz Diorite (Km) is light gray, green gray, and blue gray, weathering to yellow-brown and olive brown, fine- to coarse-grained phaneritic, approximately equigranular, predominantly moderately strong to strong, weak where sheared and mylonitized, hard to moderately hard. Locally, the quartz diorite grades to granodiorite.

3.5.2 Central Block

The Central Block corresponds to the central upper mass of the San Pedro Mountain ridge. It is bounded to the south by Fault B and to the north by Fault C. Within the Central Block, Fault 02-5 is a high angle, north dipping fault zone evident in the 02-5 rock boring. Three major lithology types are found within the Central Block unit: sandstone, conglomerate, and siltstone/claystone. Petrographic analysis indicates evidence of alteration for all rocks, likely by hydrothermal activity or weak cataclasis.

The Sandstone (Tss,a; Tss,b; Tss,c; and Tss,d) is gray to light gray, weathering to brown, lithic, moderately strong to very strong, hard to very hard, and occasional calcite-healed fractures. **Tss,a** is subangular to subrounded, fine-grained, massive to thick bedded. **Tss,b** is subangular to subrounded, fine- to medium-grained, with interbeds of weak to locally strong, mostly fractured to crushed siltstone up to 0.3 m thick. **Tss,c** is medium- to coarse-grained and massively bedded. **Tss,d** is coarse-grained, with subangular lithic fragments, pebbly, locally grading to microconglomerate.

The Conglomerate (Tc) is light to dark gray, weathering to dark brown, medium- to coarse-grained with lithic fragments, strong, hard, subangular to well-rounded clasts consisting of granodiorite, quartz diorite, quartz, sandstone, siltstone, and claystone mostly 2-8 cm in diameter with rare granitic boulders up to 1 m diameter.

The Siltstone/Claystone (Tcs,a and Tcs,b) is dark gray to black, weathering to dark brown gray, very weak to moderately strong, soft to moderately hard. **Tcs,a** is massive to indistinctly bedded; **Tcs,b** contains subangular to angular, fine-grained, thin interbeds of sandstone.

3.5.3 North Block

The North Block is located between Fault C and the North Portal. The stratigraphy of the North Block consists of an overturned sequence of well-bedded claystone, siltstone and sandstone. Rocks at the North Portal consist primarily of fine-grained sandstone with claystone and siltstone comprising only minor interbeds. But, within a short distance to the south, claystone and siltstone beds increase in abundance to form a major component of the rock mass.

Within the North Block are several faulted and sheared zones, collectively referred to as the "North Block Shear Zone". The individual shear zones contain sand-sized fragments in a clayey matrix with abundant polished and slickensided surfaces. Shear zones consisting of intensely fractured and contorted claystone beds between rigid tabular unfractured sandstone beds also occur within the North Block.

Three major lithology types found within the North Block unit are: sandstone, siltstone/claystone, and interbedded sandstone, siltstone, and claystone. Petrographic analysis indicates that all rock units show evidence of alteration by hydrothermal activity and/or cataclasis.

The Sandstone (Tss) is gray, weathering to dark brown-gray and yellowish brown, very fine- to fine-grained, subangular to subrounded grains, hard, strong, generally well-bedded with thin to medium beds commonly interbedded with dark gray to black siltstone laminae. Occasional calcite healed fractures present within the sandstone. Joint surfaces are commonly coated with calcite, iron oxide, and/or manganese oxide, and slickensided.

The Siltstone/Claystone (Tcs) is dark gray to black, weathering to dark brown gray, very weak to moderately strong, soft to moderately hard, with indistinct to well-developed to gradational thin bedding and parting.

The Interbedded Sandstone, Siltstone and Claystone (Ts) is dark gray to black, weathering to brown gray, very weak to strong, soft to hard, closely interlayered sandstone, siltstone and claystone as described above.

3.6 Structure

The overall geologic structure of the Point San Pedro-Devil's Slide area can be represented as a sequence or stack of at least three north-dipping thrust plates. The sedimentary rocks in the Central and North Blocks are further deformed by block tilting, rotation, folding, and displacement by high-angle faults. These sedimentary rocks are separated from the quartz diorite basement rock of the South Block by Fault B. Fault A, the basal thrust, is developed within the quartz diorite basement rock. The near-vertical Fault C separates unlike sedimentary rock sections, with resistant massive Central Block sandstone, conglomerate and underlying claystone-siltstone on the south and thinly interbedded sandstone and claystone-siltstone of the North Block on the north.

Within the South Block, a wide zone of steeply dipping fractures extends from the sea cliff into the South Portal rock slope and the adjacent west side of the "waterfall ravine". The strike of this fracture set is in the range of N20E to N30E. Another wide zone steeply dipping fractures with a more easterly strike, typically around N55E, governs the outline of several narrow, finger-like promontories that form the coastline directly west of the South Portal rock slope and extends into the rock mass of this slope. Fractures of this set dip steeply toward, and form acute angle intersections with, those of the N20E to N30E set. Prominent cross fractures or joints present in the lower South Portal rock slope, the upper east side rock slope, and the erosional alcove of the South Rock Cut area, each appear to be local features that do not extend to other parts of the area. The South portal rock slope cross fracture strikes NE and dips about 55^{o} NW into the slope, obliquely cutting across the portal area of the South Portal equipment chamber.

A zone of generally east-west aligned, steeply dipping to vertical shears, referred to as the North Block Shear Zone, largely defines the structural fabric of the south half of the North Block. The zone consists of approximately eleven distinguishable individual shears consisting of variably fragmented, crushed, and sheared claystone-siltstone and fine-grained sandstone, recognized in borings and in Trench 02-T3 at tunnel grade. These zones separate more or less unsheared, steeply inclined to vertical tabular bodies of claystone-siltstone and fine-grained sandstone.

3.7 Groundwater Conditions

Groundwater levels are monitored as described in the GDR. Data from these installations suggest that there are two or more semi-independent, structurally-controlled groundwater systems within each block, with the piezometric surface declining on a gradual northward gradient from a high point in the approximate center of the block. It is inferred that the Central Block piezometric surface is ponded at the boundary with the North Block, where the groundwater levels descend in a series of structurally controlled steps to the level of the valley of Shamrock Ranch.

A summary of groundwater data is given in Section 3.5.5 of the GDR. A groundwater table is shown Figure 1 interpreted from the data obtained during EMI and WCC investigations and periodic well monitoring data. Two levels of groundwater are shown in Fault Zone 02-5 based on piezometer data which indicates possible perched groundwater conditions in this area. Groundwater can be expected to fluctuate due to seasonal changes and other influences Difficult drilling conditions associated with the North Block shear zone, including groundwater inflow to borings 02-11 and 02-11A, are described in Section 3.3.4.2 of the GDR. During drilling, groundwater flow rates up to about 450 l/min were measured from the 100-mm diameter borehole collar pipe.

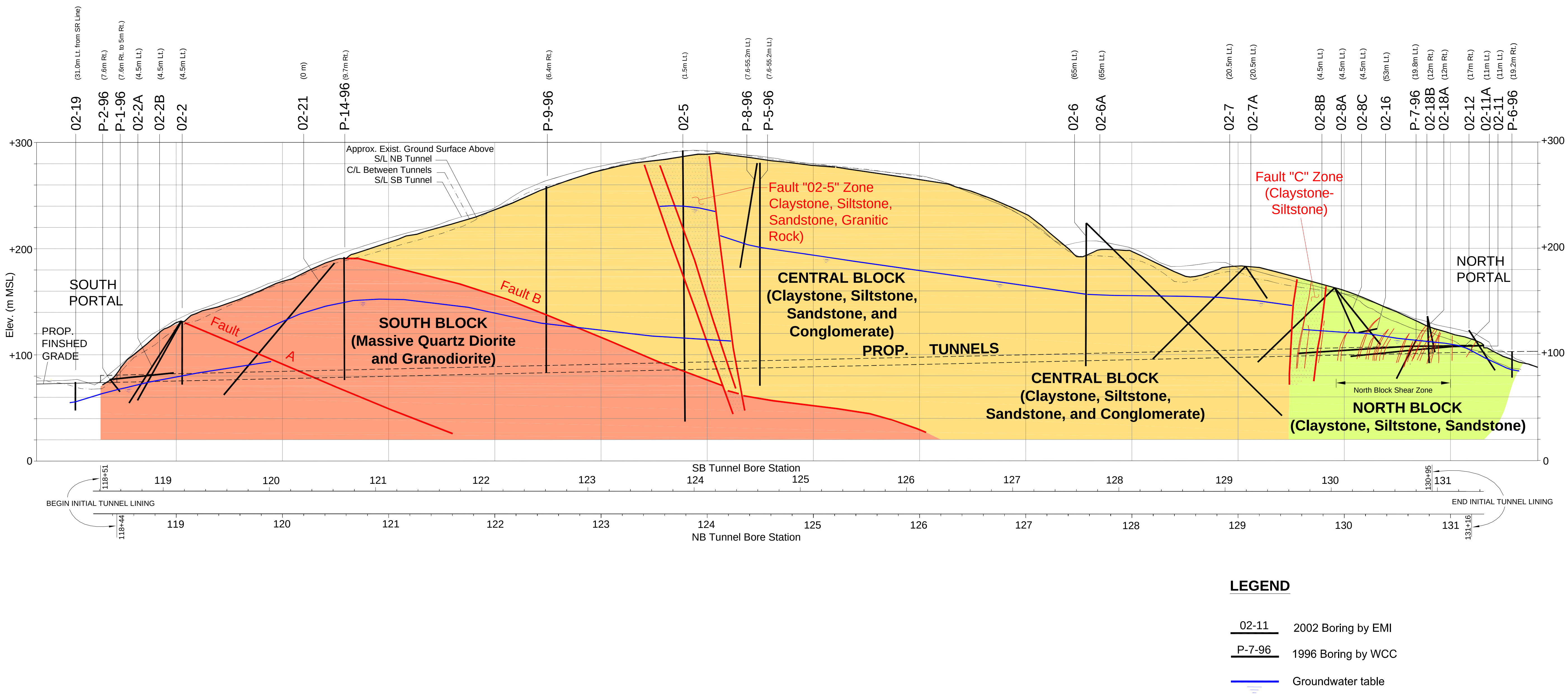


Figure 1. Geologic Cross Section along Tunnel Alignment

4.0 Ground Characterization and Baselines

4.1 Laboratory Testing

A laboratory testing program was performed to characterize the on-site rock, soil, water and air in boreholes, and to permit development of geotechnical parameters for engineering analysis and design. The tests were performed in accordance with the American Society for Testing and Materials 2001 guidelines and International Society for Rock Mechanics 1985 guidelines, unless otherwise noted. The summary tables in this section combine the test results from the WCC (1996) and EMI investigations (GDR).

4.1.1 Unit Weight

Total unit weights are summarized in Sections 4.1.2 and 4.1.3 of the GDR in table and histogram format. Generally, unit weight is affected by weathering, with more weathered samples having lower unit weight. The lowest unit weights measured were intensely to moderately weathered granitic rocks and the highest unit weights measured were fresh siltstone rocks.

4.1.2 Unconfined Compressive Strength

Unconfined Compression (UC) tests performed on intact rock cores are shown in Section 4.1.3 of the GDR in table and histogram format. Unconfined compression strengths inferred from Point Load Index (PLI) tests, along with the method used to obtain them, are given in Section 4.1.4 of the GDR in table and histogram format. The ranges and baselines of unconfined compressive strengths (UCS) q_u of intact rock are tabulated in Table 1 herein by rock type. The baselines are derived from a consideration of both UC and PLI test results. For the conglomerate moderately to intensely weathered rock the average baseline was increased to 15 MPA, because of the limited samples taken, as a conservative approach in order to alert the contractor to the possibility of encountering harder rock than was sampled and tested. Because of the limited testing data, the baseline maximum UCS was established by increasing the actual measured maximum by approximately 25% to account for the possibility that the strongest intact rock was not sampled from the exploration programs, except the baseline maximum of the moderately to intensely weathered conglomerate is derived by adding 100% to its baseline average value. The average of the unconfined compressive strength is used to determine rock mass properties. Maximum values are used as baselines for excavation methods.

Table 1. Unconfined Compressive Strength

Lithology	***Unconfined Compressive Strength, q_u (MPa)***		
	Data Range	***Average***	***Baseline Maximum***
Siltstone/Claystone, fresh to slightly weathered	2.1 to 238	30	300
Siltstone/Claystone, moderately to intensely weathered	0.1 to 34	10	40
Sandstone, fresh to slightly weathered	11.6 to 267	110	330
Sandstone, moderately to intensely weathered	9 to 73	10	90
Conglomerate, fresh to slightly weathered	3 to 239	50	300
Conglomerate, moderately to intensely weathered	0.1 to 0.3	15	30
Granitic Rock, fresh to slightly weathered	3.9 to 226	30	280
Granitic Rock, moderately to intensely weathered	0.3 to 91	7	115

4.1.3 Elastic Modulus, Shear Modulus and Poisson's Ratio

Young's modulus values are considered representative of moduli for intact rock materials. The ranges of Young's moduli obtained are presented in Section 4.1.5 of the GDR in table and histogram format.

Shear moduli *G* were obtained from pressure-meter tests as presented in Section 3.5.2.2 of the GDR in table and histogram format. This type of test represents a measure of the behavior of rock joints.

Values of Poisson's ratio are summarized in Section 4.1.6 of the GDR in table and histogram format.

4.1.4 Cerchar Abrasivity

Cerchar abrasion tests were performed on fresh to slightly weathered rock samples to provide a measure of rock abrasivity. Cerchar abrasion tests are useful in evaluating wear on mechanical cutting tools.

The Cerchar abrasion test is an International Society for Rock Mechanics (ISRM) procedure. A detailed discussion of test procedures is presented in Appendix G-4 of the GDR. The test results were categorized by tunnel segment and rock type and are summarized in Table 2. No differentiation was made between the abrasivity of the clasts and the matrix for the conglomerate samples during the test. Higher Cerchar abrasivity values indicate higher rates of wear on mechanical tools. The baseline Cerchar abrasivity values were selected as maximum values for each lithological unit as shown in Table 2. These values are somewhat higher than the maximum measured values because the limited test data may not encompass the full range of values that may be encountered along the tunnel alignment. The maximum values are used as baseline values.

Table 2. Cerchar Abrasivity

Lithology	*Cerchar Abrasivity*	
	Data Range	*Baseline Maximum*
Siltstone/Claystone	0.1 to 1.7	2
Sandstone	3.8 to 4.5	5
Conglomerate	4 and 4.3	5
Granodiorite	1.8 to 4.7	5

4.1.5 Slake Durability

The 1996 WCC investigation performed 5 slaking tests on claystone and concluded that they are generally slake-resistant. During the 2002 EMI investigation, selected rock specimens were immersed in water and showed no sign of slaking. As a result, no additional slaking tests were conducted. The baseline for slaking is that the claystone will not slake upon exposure to air or water between excavation and initial support installation.

4.2 In-situ Testing

See GDR for details of in-situ testing performed for this project.

4.2.1 Hydraulic Conductivity

Results of packer testing are detailed in Appendix C-3 of the GDR and the data is summarized in Section 3.5.4.2 of the GDR in table and histogram format. It should be noted that numerous packer tests were attempted, but could not be completed because the packers could not be seated in the fractured rock. Observations of water loss during drilling suggest that average secondary (rock fracture) permeability will be higher than the values determined by the tests that were successfully completed. Groundwater inflow is covered in Section 4.4 of this report. Baseline inflow rates are shown in Table 5.

4.2.2 Rock Quality Designation (RQD)

RQD's from the borings are presented in the boring logs (EMI, 2002 and WCC, 1996). The logs indicate that RQD generally correlates with the degree of weathering, rock type, and amount of fracturing within the various bedrock units. Regions of very low RQD (0-15%) include Fault A and Fault B in the South Block, Fault 02-5 in the Central Block, Fault C and the North Block Shear Zone. Regions of moderate to high RQD (70-100%) were found in fresh conglomerate (Tc) and massively bedded sandstone (Tss,a and Tss,c) in the Central Block, and in quartz diorite in the South Block between the Portals and Fault A.

4.3 Ground Characterization for Tunnel Section

The ground characterization is based on the determination of sections along the tunnel with consistent geological characteristics termed Rock Mass Types. To these Rock Mass Types, rock mass parameters are attributed. By considering the boundary conditions such as virgin stress, orientation of the opening with regard to geologic features, size and shape of the opening, Rock Mass Behavior Types are defined. The support categories defining the various support elements required to stabilize the opening are related to the Rock Mass Behavior Types.

During construction, the support categories shall be applied as defined on Plan S2.25. The adjustment of support elements within each support category and the selection of support categories according to actual ground conditions shall be based on the rock mass behavior observed. As means of observation, the comparison of expected and actual results of geotechnical measurement shall be used.

4.3.1 Description of Rock Mass Types

Ten Rock Mass Types were defined for the project to characterize the varying ground conditions (determined during the various soil investigation phases) for tunnel construction. The characterization is based on the relevant geological and geotechnical rock mass parameters shown in Table 3, i.e., Table 3 is to characterize Rock Mass Types.

Table 3. Geological/Geotechnical Description of Rock Type (RT)

	Range of Characteristics of Rock Mass Types (RT)				
	RT-G 1	RT-G 2	RT-G3	RT- SS1	RT-SS 2
Lithology	Granitic Rock, slightly to moderately weathered	Granitic Rock, intensely to very intensely fractured	Granitic Rock - very intensely fractured, fault zone	Sandstone, slightly to moderately weathered	Sandstone, intensely to very intensely fractured
Weathering	fresh to slightly weathered	moderately to intensely weathered	moderately to intensely weathered, with disintegration of rock, occurrence of clayey gouge common	fresh to slightly weathered	moderately to intensely weathered
Spacing of Discontinuities [cm]	10 to 50	3 to 10	<3	10 to 40	3 to 10
Persistence [m]	3 to 6	<3	<3	3 to 6	<3
Opening/infilling	slightly to moderately open, predominantly clay, few calcite and sand	slightly to moderately open, predominantly clay, few calcite and sand	slightly to moderately open, predominantly clay, some sand	tight to slightly open, predominantly calcite, few clay	tight to slightly open, predominantly calcite, few clay
RQD [%]	50 to 90	15 to 50	0 to 15	50 to 90	15 to 50

	Range of Characteristics of Rock Mass Types (RT)				
	RT-SH 1	RT-SH 2	RT-SH 3	RT-C 1	RT-C 2
Lithology	Interbedding of Siltstone and Claystone with Sandstone and Conglomerate interbeds possible	Interbedding of Siltstone and Claystone with Sandstone and Conglomerate interbeds possible	heavily sheared and disintegrated Claystone and Siltstone (fault gouge) with more competent blocks of Sandstone and Conglomerate (block in matrix structure)	Conglomerate, slightly to moderately weathered	Conglomerate, intensely to very intensely fractured
Weathering	fresh to slightly weathered	moderately to intensely weathered	intensely weathered to disintegrated	fresh to slightly weathered	moderately to intensely weathered
Spacing of Discontinuities [cm]	10 to 40	<3	NA	10 to 50	3 to 10
Persistence [m]	3 to 6	<3	NA	3 to 6	<3
Opening/infilling	tight to slightly open, predominantly calcite, few clay	tight to slightly open, predominantly calcite, few clay	NA	tight to slightly open, predominantly calcite, few clay	tight to slightly open, predominantly calcite, few clay
RQD [%]	50 to 90	15 to 50	0 to 15	50 to 90	15 to 50

Table 4 lists the relevant rock mass parameters defined for the individual rock mass types. The range of parameters listed is the basis of initial support calculations.

Table 4. Characteristic Rock Mass Parameters

Rock Mass Parameters						
Parameter	Unit	RT-G 1	RT-G 2	RT-G 3	RT-SS1	RT-SS2
Density	γ [KN/m³]	25-27	22.5 – 25.5	22.5 – 25.5	25-27	25-27
Young's Modulus	E [GPa]	2-4	0.4 – 0.8	0.2 – 0.4	4 – 6	0.5 – 1.0
Cohesion	c [MPa]	0.4 - 0.6	0.15 – 0.25	0.05 – 0.15	0.7 – 1.0	0.2 – 0.3
Angle of internal friction	Φ[°]	35 - 40	25 - 30	15 - 25	40 - 50	20 - 30

Rock Mass Parameters						
Parameter	Unit	RT-SH1	RT-SH2	RT-SH3	RT-C1	RT-C2
Density	γ [KN/m³]	25-27	25-27	23 – 25	25-27	25-27
Young's Modulus	E [GPa]	1-2	0.5 – 1.0	0.03 – 0.05	3 – 5	0.5 – 1.0
Cohesion	c [MPa]	0.25 - 0.35	0.15 – 0.25	0.01 – 0.02	0.6 – 1.0	0.2 – 0.3
Angle of internal friction	Φ[°]	25 - 30	20 - 25	20 - 25	40 - 45	25 - 30

4.3.2 Behavior Types

Four different Behavior Types are identified relevant to the project. The behavior types describe the rock mass behavior during full face construction without support. The behavior types are defined based on the characteristics of the rock mass types taking the groundwater conditions, stress conditions and orientation of the main discontinuity sets relative to the tunnel structure into account.

Behavior Type 4 applies to both support categories IV and V by differentiation of the intensity and progress of stress failure.

Figure 2. Behavior Type 1: Failure mode of falling rock blocks

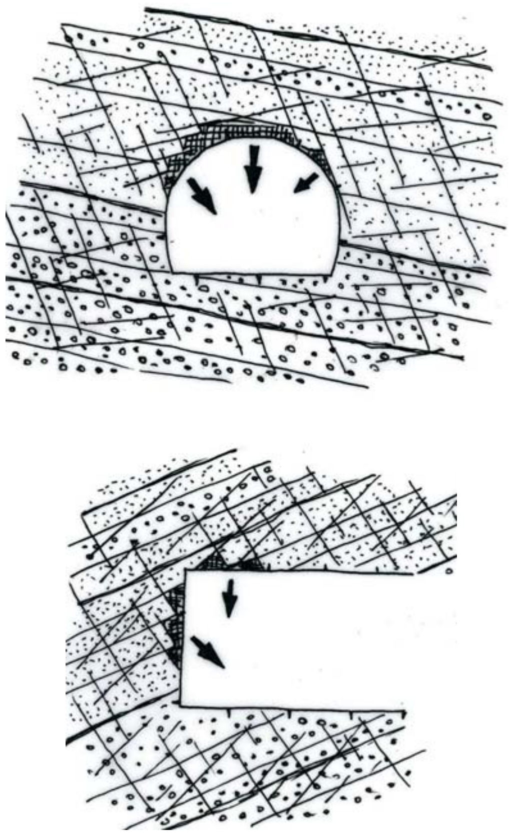
Failure Mode	Description
	Failure of rock blocks (blocky ground): The failure is induced by interaction of discontinuities after excavation of each round, resulting in falling out of individual blocks.

Figure 3. Behavior Type 2: Fracturing induced by stresses and/or discontinuities

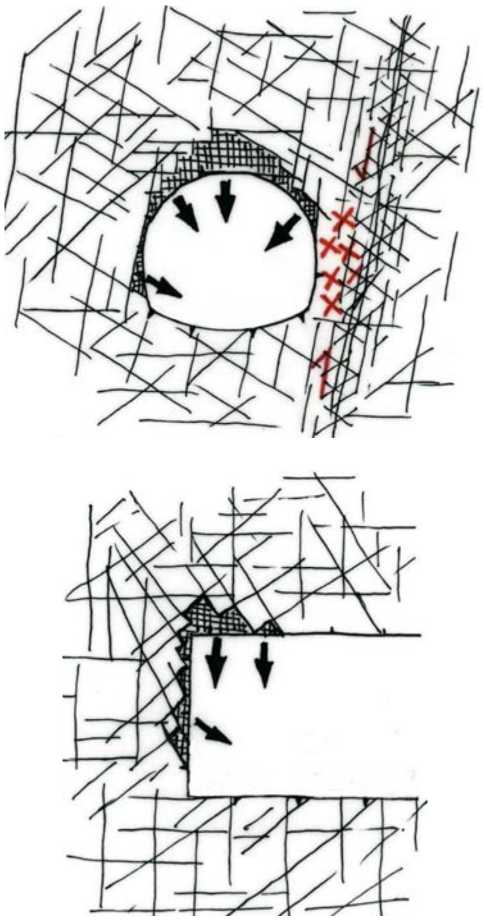
Failure Mode	Description
	Fracturing induced by discontinuities (blocky and seamy ground): The rock mass behavior is characterized by shear failure along discontinuities at the crown and the tunnel walls, due to the movements along discontinuities the rock mass is loosened. Mostly vertical loads are activated (loosening pressure).

Figure 4. Behavior Type 3: Progressive stress induced failure mode

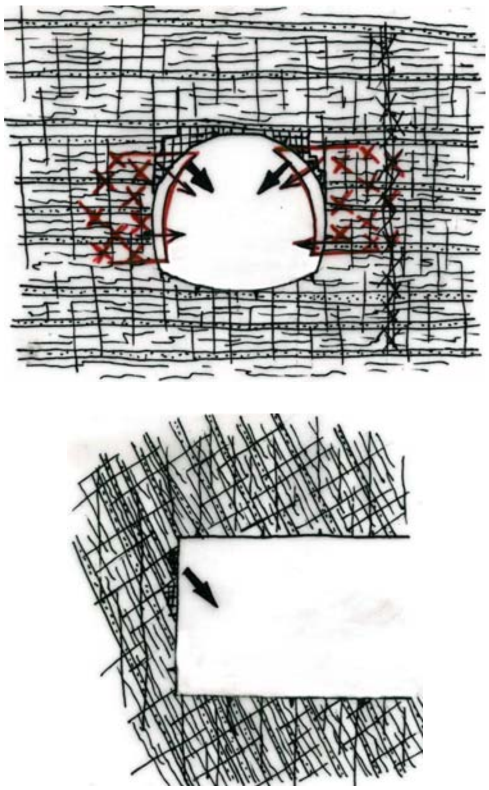
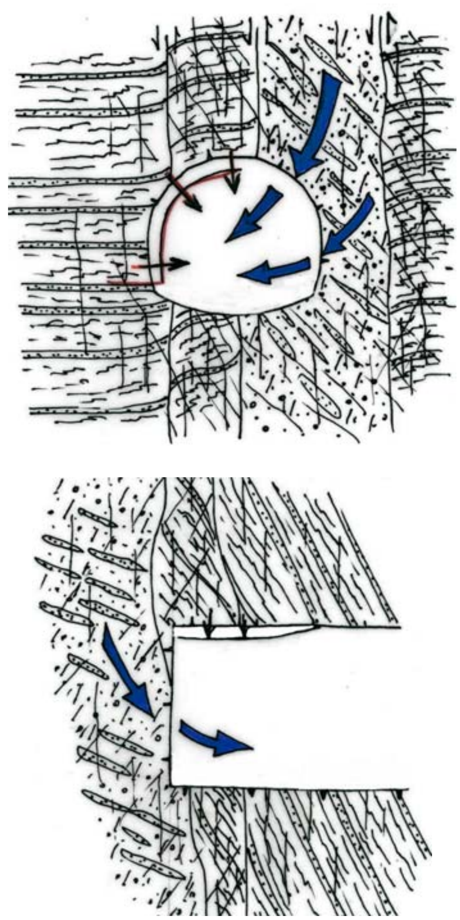
Failure Mode	Description
	Progressive failure induced by stresses (squeezing ground): The rock mass undergoes progressive failures from shear stresses, resulting in progressive deformations as the load bearing capacity of the rock mass is exceeded.

Figure 5. Behavior Type 4: Groundwater induced failure mode ahead of the tunnel face

Failure Mode	Description
	Progressive failure induced by stresses ahead of the tunnel face (fast raveling ground): Weak, incompetent ground, results in rock mass piping and failure developing ahead of face. In addition, groundwater will deteriorate the ground, worsening the stability of the face.

4.4 Groundwater Inflow

4.4.1 Flush Flow for Heading of Tunnels

Flush flow is defined as water ingress over a 20 m long section, ahead of the tunnel face, from localized zones of highly permeable rock or individual features such as joints and shear zones in the rock mass. In the case where a fault is encountered, the flush flow will suddenly increase due to the release of water beyond a low permeable layer. Flow is assumed to decrease with time until it is reduced to the steady state inflow.

The following table shows baseline values for the flush flow relevant for the individual tectonic units along the tunnel alignment.

Table 5. Flush Flow Baseline Values for both Tunnels

	1st Heading North Bound [l/s*20m]		2nd Heading South Bound [l/s*20m]	
Tectonic Unit	**Rock Mass**	**Fault Zone**	**Rock Mass**	**Fault Zone**
South Block	3	8	1.5	3.5
Central Block	3	12	1.5	3.5
North Block	3	15	1	6

Two major faults are expected in the South Block (faults A and B), one major fault in the Central Block (fault 02-5), and three major faults or shear zones in the North Block (fault C plus two major shear zones). Probe and drain holes drilled into the tunnel face in the advancing direction will shift water inflow to the tunnel face when water bearing zones are encountered. Inflows from these holes are included in the baseline values established for flows from fault zones.

4.4.2 Steady State Inflow at the end of Tunnel Construction

Water inflow decreases considerably over time. The flush flow in fault zones of the first tunnel heading, for instance, will decrease by one half within two weeks. As baseline, 50 l/s is defined as the maximum inflow from both tunnels after excavations have been completed.

5.0 Support/Design Considerations

5.1 Initial Support

The required support measures to encompass all anticipated ground conditions are differentiated in five support categories as shown on the Plans. The distribution of the support categories along the tunnel alignment shown on the Plans are for bid purposes only and shall be determined based on the actual ground conditions encountered.

Table 6 provides the length and percentages of the support categories for bidding purposes:

Table 6. Support Category Distributions

Support Categories	SB Tunnel	NB tunnel
I	317 m (25 %)	311 m (24 %)
II	488 m (39 %)	499 m (39 %)
III	295 m (24 %)	274 m (22 %)
IV	107 m (9 %)	136 m (11 %)
V	37 m (3 %)	52 m (4 %)
Total	**1244 m**	**1272 m**

Criteria for the application of support categories are shown on Plan S2.25.

6.0 Construction Considerations

6.1 Excavation Sequence

Excavation shall start at the south portals and proceed northward. The NB tunnel shall be excavated first followed by the SB tunnel as shown on Plan S2.1. Distances between excavation faces of the two tunnels will be maintained as shown on the Plans.

Excavation construction sequencing of the NB and SB tunnels for various support categories is included in the Plans. The southern and center equipment chambers shall be excavated only after the NB and SB tunnels, cross passages, and access tunnels have all been excavated and their support systems fully functional.

The boreholes for cable conduits between the north equipment chamber and the enlarged NB tunnel tube shall be drilled after the tunnel is fully supported.

6.2 Portals Construction

At the South Portals, before excavation commences, short shotcrete canopies shall be erected as protection against raveling rock. At the North Portals, the construction and backfilling of the cut & cover section shall be completed before the NB and SB tunnels are excavated through these portal sections. In addition, short shotcrete canopies shall be erected at the North Portals as protection against raveling rock.

6.3 Probe Hole Requirements

Probe hole requirements, locations and details are shown on the Plans. Additional probing is important when nearing fault zones and in difficult ground.

6.4 Geotechnical Measurements

Geotechnical instrumentation allows for the assessment and monitoring of ground deformations during and after excavation.

Geotechnical readings shall be compared with expected deformations. This process, together with visual observations, is essential for the decision making process of the determination of ground support categories. The various types of geotechnical instrumentation are detailed in the Plans and Specifications including the locations, installation and monitoring procedures.

The types of instrumentation include:

- Lining deformations using Optical Targets
- Multi Point Borehole Extensometers for monitoring Rock Mass Deformations
- Measuring Rock Bolts performance
- Pressure Cells to monitor actual load on shotcrete lining

6.5 Ground Water Control

The construction sequence, starting from the south portals working north, allows the groundwater/formation water to flow by gravity to the south portals. Groundwater flows into the tunnels through the rock dowel boreholes and cracks in the shotcrete lining, as well as through weep holes drilled through the shotcrete lining near the longitudinal drain pipes as shown in the Plans. Dewatering ahead using horizontal drainage holes drilled through the excavation face, as shown on the Plans, is essential in those areas where high water ingress is expected. It is the intent of these documents that groundwater will be controlled by these methods.

The ingress water shall be channeled into trenches along each side of the tunnels out of the way of excavation and transportation systems. Water shall be diverted into a collection basin at the South Portal where it will be monitored for contamination and treated to meet required criteria prior to discharge.

6.6 Ground Improvement

Ground improvement or ground stabilization ahead of the excavation will be needed in specific areas for safe excavation of the tunnels as shown on the Plans. This ground improvement includes the installation of spiles, steel pipe arches, and dewatering ahead of the face. Face dowels shall be installed where needed to control stability of the face.

6.7 Sources of Potential Failures:

It shall be noted that the interruption of the excavation process for holiday breaks and/or weekends, allows time dependent stress re-distribution. For this reason, strengthening of the initial support near the face shall be required.

Due to the fact that disturbed zones or weak zones or high water ingress will be abruptly encountered even when probe holes are provided, the contractor shall provide contingencies of sufficient material and equipment on hand to deal with this and other unexpected events, such as the placing of additional support to previous placed initial supports if deformation exceeds limiting values.

7.0 Appendix

7.1 References

Earth Mechanics, Inc. (2002) [GDR], “Geological and Geotechnical Data Report, Devil’s Slide Report”, Report to California Department of Transportation, December.

Woodward-Clyde Consultants (1996), “Devil’s Slide Tunnel Study, Final”, Report to California Department of Transportation, August/September.

7.2 Project Geological Glossary

Bed: A distinct layer of sediment or sedimentary rock greater than 1 cm in thickness.

Bedding plane: In sedimentary or stratified rocks, a surface that separates each layer from those above or below it. It usually records a change in depositional circumstances by grain size, composition, color, or other features. The rock may tend to split or break readily along bedding planes.

Behavior Type (BT): Rock Mass with similar behavior with respect to the failure mode during excavation before installation of any support.

Bedding joint: A narrow crack in a rock, along which there has been no significant movement, parallel to the bedding planes formed by tectonic processes.

Block-boundary faults: Fractures in the earth’s crust along which significant movement has occurred that separate coherent land masses.

Claystone: Non-fissile, fine-grained rock consisting of compacted particles, at least two-thirds of which are less than about 0.004 mm in size.

Clayey sand: In accordance with the USCS soil classification, a coarse-grained soil containing less than 15% gravel (greater than 2 mm in size) and more than 12% clay particles (less than 0.004 mm in size).

Closely spaced: with discontinuity spacing of 3 to 10 cm.

Conglomerate: Sedimentary rock made of at least 20% rock fragments greater than 2 mm in size in a finer-grained matrix.

Decomposed: Discolored or oxidized throughout, with all feldspars and iron-magnesium minerals are completely altered to clay; complete separation of grain boundaries; resembles a soil and may be granulated by hand; partial or complete remnant rock structure may be preserved.

Discontinuity: Surface across which properties of the rock mass are discontinuous.

Extremely widely spaced: With discontinuity spacing of more than 3 m.

Fault: A fracture in the Earth along which one side has moved in relative to the other.

Fault gouge: Mixture of crushed rock and fine-grained alteration minerals (clays) formed as the rough surfaces of rock on either side of a fault slide past one another.

Fault zone: An area with multiple faults.

Flush inflow: Initial tunnel inflow occurring over a 20 meter long heading section of the tunnel; the amount of water to be expected can vary significantly depending on the permeability of the encountered rock mass.

Fracture: Any break in rock along which no significant movement has occurred.

Fresh: Rock having no evidence of discoloration or oxidation, grain boundaries within the rock are intact and no alteration of texture has occurred.

Friable: Rock can be easily broken using only manual pressure.

Granite: A coarse-grained intrusive igneous rock with at least 65% silica. Quartz, plagioclase feldspar and potassium feldspar make up most of the rock and give it a fairly light color. Granite has more potassium feldspar than plagioclase feldspar. Usually with biotite, but also may have hornblende. Granite is actually quite rare in the U.S.; often the term is applied to any quartz-bearing plutonic rock.

Granitic: A general term for intrusive igneous rocks that look similar to granite but may range in composition from quartz-diorite to granite. All granitic rocks are light colored; feldspar and quartz are visible in hand specimen.

Granodiorite: A coarse-grained intrusive igneous rock similar in composition to granite, but containing more plagioclase than potassium feldspar.

Hard: Describing rock that can only be scratched with a knife with great difficulty. Heavy hammer blow is required to break specimen.

High-angle fault: Fracture in the earth's surface with a dip of greater than approximately 45^{o}.

Igneous: Any rock solidified from molten or partly molten material.

Interbed: Layer of rock lying between or alternating with layers of a different kind of rock.

Intensely weathered: Describing rock with discoloration or oxidation throughout; all feldspars and iron-magnesium minerals are altered to clay to some extent. Chemical alteration produces in-situ disaggregation. Rock can be broken with manual pressure of by light hammer blow without reference to planes of weakness such as incipient or hairline fractures.

Joint: A narrow crack in rock along which there has been no significant movement of either side. Joints commonly form in parallel sets.

Laminated: With very thin layers of bedding less than 1 cm thick.

Lithology: The description of rocks on the basis of such characteristics as color, structure, mineralogic composition and grain size. Generally, the description of the physical character of a rock.

Massive: With bedding more than 3m thick.

Microconglomerate: A sedimentary rock composed of relatively coarse sand grains in a very fine silt or clay matrix.

Moderately bedded: With bedding 10 to 30 cm thick.

Moderately hard: Describing rock that can be scratched with a knife or sharp pick using light or moderate pressure. Breaks with moderate hammer blow.

Moderately rough: Surface unevenness is clearly visible and fracture surface feels abrasive.

Moderately soft: Describing rock that can be grooved 2 mm deep by knife or sharp pick with moderate or heavy pressure. Breads with light hammer blow or heavy manual pressure.

Moderately spaced: With discontinuity spacing of 10 to 30 cm.

Moderately weathered: Discoloration or oxidation extends from fractures usually throughout. Iron-magnesium minerals are rusty in appearance and feldspar crystals are cloudy. All fracture surfaces are discolored or oxidized and soluble minerals may be mostly leached. Hammer does not ring when rock is struck. Body of rock is slightly weakened.

Mudstone: A very fine-grained, nonfissile sedimentary rock in which the proportions of clay and silt are approximately equal.

Quartz diorite: A group of igneous rocks having the composition of diorite but with an appreciable amount of quartz, i.e., between 5% and 20% of the light-colored constituents; also, any rock in that group; the approximate intrusive equivalent of dacite.

Resistant: Describing rock that does not easily weather, deform, or fracture.

Rock: Aggregate, consisting of mineral components, developed from natural processes.

Rock Mass: Part of the earth's crust, composed of rock and/or soil, including discontinuities, anisotropy, and voids filled with liquids or gases.

Rock Mass Type (RT): Rock Mass with similar rock and discontinuity properties.

Rough: Large surface unevenness and irregularity is clearly visible and fracture surface feels abrasive.

Sand*:* Loose particles of rock or mineral (sediment) that range in size from 0.0625 to 2.0 mm in size.

Sand with silt: In accordance with the USCS soil classification, a coarse-grained soil containing less than 15% gravel (greater than 2 mm in size) and 5-12% silt particles (0.1-0.004 mm in size).

Sandstone: A medium-grained clastic sedimentary rock composed of fragments of sand size set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material (commonly silica, iron oxide, or calcium carbonate); the consolidated equivalent of sand. The sand particles usually consist of quartz, and the term sandstone, when used without qualification, indicates a rock containing about 85% to 90% quartz.

Shale: Sedimentary rock derived from mud. Commonly finely laminated (bedded). Particles in shale are commonly clay minerals mixed with tiny grains of quartz eroded from pre-existing rocks.

Shear(ed): Rock deformation involving movement past each other of adjacent parts of the rock and parallel to the plane separating them.

Shear zone: Region of rock with deformation across thickness involving movement past each other of adjacent parts of the rock and parallel to the plane separating them.

Siltstone: Sedimentary rock lacking fissility in which the mud fraction is over 2/3 silt (0.004 to 0.062 mm).

Slickensided: Describing rock discontinuity surfaces with scratches or grooves.

Slightly rough: Surface unevenness is present.

Slightly weathered: Discoloration or oxidation limited to surface or short distance from fractures; some feldspar crystals are dull. Minor leaching some soluble minerals. Hammer rings when crystalline rocks are struck; body of rock not weakened.

Smooth: No surface unevenness, surface is not rough to the touch.

Soft: Grooved or gouged easily by knife or sharp pick with light pressure, can be scratched with fingernail. Breaks under light to moderate manual pressure.

Solid Rock: Mineral aggregate, whose properties pre-dominantely are determined by the physical / chemical bond.

Steady state Inflow : Condition when the water table drawdown drops to the elevation of the tunnel crown and established water inflows only change due to seasonal fluctuations.

Stepped: Describing rock discontinuity surfaces with near-normal steps and ridges.

Strike: The direction or trend of a bedding plane or fault, as it intersects the horizontal.

Strike-slip fault: General term for a vertical or nearly vertical fault with horizontal displacement vector producing lateral relative motion of the rock on either side.

Structure: A geological feature produced by deformation of the Earth's crust, such as a fold or a fault; a feature within a rock, such as a fracture or bedding surface; or, more generally, the spatial arrangement of rocks.

Thin(ly) bedded: With bedding 3 to 10 cm thick.

Thick(ly) bedded: With bedding 30 cm to 1 m thick.

Thrust: Fault in which the upper block above the fault plane moves up and over the lower block, so that older strata are placed over younger.

Thrust sheets: Slab of rock, generally on the scale of a mountain or more, bounded by two thrust faults.

Vergent: Describing the direction toward which a fault or fold is overturned or inclined.

Very closely spaced: With discontinuity spacing of less than 3 cm.

Very hard: Describing rock that cannot be scratched with a knife or sharp pick. Breaks with repeated hammer blows.

Very soft: Describing rock that is readily indented, grooved, or gouged with fingernail, or carved with a knife. Breaks under light manual pressure.

Very thin(ly) bedded: with bedding 1 to 3 cm thick.

Very thick(ly) bedded: With bedding 1 to 3 m thick.

Very wide(ly) spaced: With discontinuity spacing of 1 to 3 m.

Wide(ly) spaced: With discontinuity spacing of 30 cm to 1 m.